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Investigating the Relationship Between Moisture Content and Dry Density on Different Gradations for Road Base Granular Materials

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Abstract: California Bearing Ratio (CBR) in granular materials is the key technical characteristic of layers in flexible pavement. The CBR value is a way to measure the material stiffness used in the pavement design procedure for the road base layer depending on the aggregate types. Road base layers' ultimate role in the flexible pavement is to spread loading evenly over the sub-grade from the loading of vehicles throughout the design life. Among the factors affecting the material's bearing capacity, aggregate gradations are one of the most important parameters that give a considerable result. This study was carried to evaluate the effects of different aggregate gradations using granite, basalt, and quartzite aggregates on the bearing capacity of the granular materials. Further analysis on the base course layer's upper and lower gradation limit were conducted to identify the bearing capacity of the layer, through a series of aggregates physical tests and strength tests. The results indicated that physical properties of the selected aggregates complied to the Public Works Department (PWD) Specifications (2008) for soaked and un-soaked condition. For both soaked and un-soaked conditions, the samples with lower limit gradations showed higher stress values compared to upper limit gradations for all three types of aggregates. Granite showed higher CBR values for both, soaked, and un-soaked conditions, followed by basalt and quartzite at upper and lower limit gradation. Un-soaked granite samples with lower limit gradation showed 60.5% increment in strength compared to un-soaked upper limit gradation, followed by quartzite 53.6% and basalt 9.94% respectively. The results indicated that strength is highest in the lower limit gradations where the use of coarse-grained aggregates could significantly increase the strength.

Keywords: Aggregates, gradations, road base, CBR

1. Introduction

Aggregates used for highway construction are commonly obtained from local supplies of natural rock. Natural rocks are classified into igneous, sedimentary and metamorphic based on their origin by geologists. The most important characteristics of the rocks relate to how well the aggregates serve in the various applications such as sub-bases, bases, or in various HMA courses used for pavement construction. Therefore, for the most part, the physical properties of the

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aggregates are the most important factors that need to be considered for highway construction. Since the natural rock material is from different sources or areas within a quarry or gravel pit can vary, it is important to test the aggregate samples regularly to ensure that the aggregate properties meet the specified standards and are consistent. Aggregates' physical characteristics, such as resistance to abrasion and strength are determined primarily by the characteristics of the parent rock. However, the production process in the quarry can significantly affect the quality of the aggregate by eliminating weaker rock layers and by crushing on the particle shape and gradation of the aggregate [1]. The basic purpose of a quarry operation is to remove sound rock from the face quarry by blasting and then using a series of crushers, pulverisers, and screening units to size the materials into a sufficient aggregate size to produce the desired pavement construction materials. It is also desirable to produce crushed aggregate that is essentially cube-shaped and not flat or elongated.

The quality of aggregates can have a significant impact on the performance of the pavement. The low stiffness of the base layer and the results of excessive rutting in the pavement are often caused by the quality of the material used for road construction. Pavement engineers commonly use aggregate quality to describe the suitability of an aggregate for use in road construction, while highway agencies commonly use density and proof rolling to determine the quality of base layers. However, different approaches may exist for classifying aggregate materials and rating the quality of an aggregate for structural layer function [1]. Furthermore, different aggregate sources can be classified as meeting the same specification as long as the material meets the gradations requirements even though they may have varying physical properties affecting performance. Effects of physical shape, texture, and angularity of aggregate particles, in addition to gradation, on the strength, stability, and performance of unbound pavement layers are often not considered in the current practice. The reason might be due to the lack of accurate and repeatable measurements of the coarse aggregate morphology in the past [1].

Physical properties determine the suitability of aggregate for different use in pavement construction and govern aggregate durability and soundness. The performance of granular materials depends on the interaction between aggregate source, gradation, and fines content. In addition to these parameters, other factors have a significant effect on base material performance. The other factors are plasticity of fines, degree of compaction, moisture content, and aggregates shape, texture, and angularity [2]. Saeed et al. [3] specified several laboratory tests that measure properties related to the performance of aggregates as granular base materials such as particle size distribution, moisture content-density relationship, Atterberg limits, toughness, and abrasion resistance, soundness, elastic modulus, and shear strength.

One of the primary variables in any laboratory testing of aggregate materials is the grain size distribution. Gradation itself is the key factor influencing the mechanical response behaviour characterized by resilient modulus, shear strength, permanent deformation, permeability, frost susceptibility, and erosion susceptibility. Aggregate gradation is also critical to achieving good packing and thus stability in an aggregate mix. Differences in aggregate gradations can often lead to significantly different performances for the same aggregate type. This is due to the different pecking order and void distributions that play a crucial role in load-carrying through particle to particle contact in an aggregate matrix. Thom et al. [4] found that the effect of grading varied with the compaction level. Brown et al. [5] successfully reduced rutting in granular base layers by selecting optimum aggregate material grading which has maximum compacted density. Bilodeau et al. [6] identified, from a laboratory study conducted on unbound granular materials with six gradations and three aggregate sources commonly used in Canada, one fines-related volumetric parameter (termed fine fraction porosity) that described satisfactorily not only the mechanical performance but also the environmental stress sensitivity of materials tested. Also identified from their study were the optimized gradation zones that ensured adequate overall performance of those three aggregate sources.

The aggregates for use in road base course construction shall be either crushed stone, crushed or un-crushed slag, crushed or un-crushed gravel and sand [7]. By using low-quality aggregates, the performance of the pavement could be adversely affected. The main functions of these granular materials are to protect the underlying weak sub-grade through the interlocking aggregate. Different aggregate types and aggregate sizes have different effects on granular material for road base courses. The effects of different aggregates as road base materials on bearing capacity can be evaluated by performing California Bearing Ratio (CBR) test. The stronger materials give the higher CBR readings, the less thickly the road surface must be designated and built.

This paper presents the results of CBR on different types of granular materials for road bases. Upper and lower gradations have been applied to evaluate the mechanical behaviour of these granular materials. The following sections describe the material’s properties, experimental methodologies employed and the CBR values for both, soaked and un-soaked conditions.

1.1 Road Base Granular Materials

The road base materials are structurally intended to support the traffic load without causing excessive distress in subsequent layers. One of the factors that affect the strength of the base course depends on the properties of the aggregates themselves. Thus, accomplishing the function of the road base, high density layer, and stability aggregates are required. To gain stability and durability of the base course structure, an aggregate with slight or no fines content is considered aggregate that possesses higher resistance to deformation from the grain-to-grain contact [8].

The granular base and sub-base layers must function as both a short-term construction platform and long-term durable structure for the overlying pavement [9]. In developing countries, the main structural pavement element is formed by granular layers with a thick base and sub-base layers placed over the subgrade. These layers protect the pavement structures against water ingress.

According to Siripun et al. [10], roads have been subjected to the changing of traffic load characters resulting in a pavement premature failure, and consequently, there are more complexities of pavement loading conditions and the current pavement analysis insufficient in predicting reliable pavement behaviors. In practice, deteriorations in the pavement can take place in base and sub-base layers if improper materials are utilized. The top and bottom parts of an asphalt layer are subject to the changes under traffic because of the bending from the vehicle movement leading to, in both parts, the transformation of tension to compression and being back to tension after returning to its original contour [11]. The current pavement analysis of base and sub-base courses is considered only the vertical compressive stress distribution to the multilayers of pavements which the magnitude of stresses takes place in sub-layers depending on each elastic stiffness of pavement materials with a given layer thickness. These design procedures focus on designing the asphalt layer, given the subgrade condition, the traffic loadings, and the climatic conditions. In the industrialized countries, where these design procedures originate from, the main structural element is the asphalt layer. As Sweere [12] noted, the Shell Pavement Design Manual is a clear illustration of this: through the fixed ratio of the stiffness of the (sub-) base and the subgrade, the structural contribution of the unbound granular (sub-) base is limited and granular materials hardly play a role in the design. The bearing capacity of granular materials is a result of the shear resistance of the aggregate skeleton i.e., through aggregate interlock between particles.

To understand pavement, it is fundamental to have a better perception of the materials used in the pavement design on material characterization and corresponding performance in pavement design. This requires an empirical test to evaluate the strength, durability, and stability of the pavement design. This is done through understanding the properties of the aggregate. These design procedures focus on designing the asphalt layer, given the subgrade condition, the traffic loadings, and the climatic conditions. This is because, in the industrialized countries, where the design procedures originate, the main structural element is the asphalt layer and the significance of the granular base and sub-base are virtually reduced to that of a working platform. CBR is used in determining the bearing capacity and the CBR value of the materials at their optimum moisture content used as an aid in the pavements design. The CBR test was developed by the California division of highway in 1929 to predict the behaviour of materials in the pavement and cane performed both in the laboratory and in-situ [13]. The bearing capacity of granular materials is a result of the shear resistance of the aggregate skeleton i.e. through aggregate interlock between particles.

In developing countries, including Malaysia the granular materials extensively used for base layers are to distribute the wheel load pressure from the surface layer. In Malaysia, the Specifications of Road Works (JKR/SPJ/1988) is "recipe-based" specifications that require flexible pavement materials to comply with the physical properties described in the specifications. The increasing number of vehicles and the number of repetitions on the pavement, cause permanent deformation of the pavement structure in current situations. To overcome and reduce the problems of road distresses, JKR has revised the JKR/SPJ/1988 and has come up with a new JKR/SPJ/2008. Amendments have been made to the material's requirements and the gradations. For the design purpose, Arahan Teknik Jalan 5/85 (Pindaan 2013) supersede the existing JKR pavement design manual (Arahan Teknik Jalan 5/85) which is based on Asphalt Institute and AASTHO design procedures after undergone several revisions. In Malaysia, the government has to spend every year in maintenance and rehabilitation of roads where most of the roads are facing road defects such as permanent deformation (rutting), fatigue, etc. The road design standard was not updated or improved consistently, as in Manual of Pavement Design by JKR (Public Work Department) Arahan Teknik Jalan 5/85, which was used for almost more than 20 years without any modifications. Due to the previous and current distresses experienced, the JKR Mix Design standard has been reviewed due to the high traffic loading which causes pavement failures (mainly subgrade failures).

This study is an attempt to determine the effect of gradation and moisture-density, of various types of base materials on the CBR value. To better evaluate the effect of different amount of coarse and fines on the strength of the base materials as road base layer, a laboratory study has been conducted. The CBR tests were conducted at both conditions, soaked and un-soaked in order to determine the strength of the base materials at normal and worst condition. A base material that complies with the required specification, is associated with better load-taking ability, thus influence the strength of the base layer. In addition, the application of basalt and quartzite as road base materials is less practiced compared with granite and also there is lack of studies conducted on these materials.

2. Materials and Methods

All the steps of this research are described below, and the results are as shown. This study was based on experimental laboratory activities and the first step was obtaining the natural granular material (aggregates) from local quarries in Peninsular Malaysia. The properties tests were the first activity carried out to check the material's properties based on the PWD requirements for road base material's specification, and the test results were also compared with AASTHO specifications. Type I gradation was selected in this study as specified in JKR 1988 specification, and the materials included is in the gradation's range as per PWD specification which was determined through particle size distribution. Proctor test was conducted to determine the optimum moisture content (OMC) and the maximum dry density ($\gamma_{dry\ max}$) of these materials. The OMC value needs to be set as it is a clue to the compaction activity in the field. The final laboratory test of the whole process was the CBR test, which was to determine the CBR value, for both soaked and un-soaked conditions for all the materials. The road base materials compacted were soaked in water for 96 hours or 4 days before testing. Lastly, the moisture-density relationship with CBR value have been elaborated in this study.

2.1 Material Properties

The granular materials that were used in this research were granite, obtained from a quarry in Minyak Beku, Batu Pahat, next basalt which was obtained from a quarry in Temerloh, Pahang, and quartzite from the quarry in Jitra, Kedah. To test the hypothesis, all the three aggregates were evaluated to comply with the PWD's Specifications [7] and AASTHO Standards [14]. Table 1 and Table 2 show the technical specifications for the road base materials. The selected aggregates comply to the PWD requirements (Table 1) and AASTHO Standard (Table 2) for base coarse layer aggregates.

Table1 - Technical specifications for wet mix road base according to PWD Road Work Specifications (2008) for selected aggregates [7]

Test*	PWD Specifications	Aggregate Types		
		Basalt	Granite	Quartzite
PI	≤ 6	*NP	NP	NP
Flakiness	≤ 25	19	15	22
ACV	≤ 25	16	22	23
CBR	≥ 80	-	-	-
SE	≥ 45	53	53	85

*(PI = Plasticity Index (BS 1377), SE=Sand Equivalent (AASTHO T176), ACV=Aggregate Crushing Value (BS 812), CBR=California Bearing Ratio (AASTHO T193) [15]

Table 2 - Technical specifications for road base according to AASTHO

Test	AASTHO Specifications	Aggregate Types		
		Basalt	Granite	Quartzite
LOS	Max. 45	16	22	37
AIV	Max. 35	14.63	21.91	22.7
LL	Max. 25	13.4	24.07	18.72

*(LOS = Los Angeles Abrasion Test (AASTHO T90), AIV = Aggregate Impact Value (ASTM D5874), LL = Liquid Limit (AASTHO T89).

2.2 Particle Size Distribution

Type I gradation as per Standard Specification for Road Works [7] for road base materials has been applied in this study and from the Type I gradations, two level of gradation limit been applied which is upper limit and lower limit. The ratio of coarse aggregate and fine aggregate for upper and lower limit are 40:60 and 60:40 respectively. Amount of coarse and fines aggregates for road base materials plays an important role in interlocking the particles when compacted, thus influence the strength of the base layers. The objective of this study was to identify the effect of different aggregate gradations on bearing capacity as road base materials. Table 3 shows the gradation limit as per PWD Specification and of the selected aggregates. The particle size distributions of the selected aggregates are within the gradation limit as per PWD Specifications as shown in Fig. 1.

2.3 Compaction Characteristics

The compaction test conducted on these aggregates were the Modified Proctor Test following AASTHO T180 [14]. The principle is to compact the materials at different water content and compaction energy corresponding to 62 blows per layer. The moisture content and the maximum dry density of the upper and lower limit gradations for each aggregate were determined. From these two parameters, the compaction curves were plotted.

Fig. 2 and Fig. 3 represent the curves of compaction and compaction parameters. Meanwhile, Table 4 shows the optimum moisture content for upper and lower limit gradation for all three types of aggregates. The optimum moisture content for the upper limit gradation of all the aggregates is higher compared to the lower limit gradation. The lower limit gradation of the aggregates is more sensitive to water because when there are larger (coarse) aggregates with more surface areas and more fines, thus these will allow more water absorption, where the ratio of coarse and fine aggregates for lower and upper gradations are 60:40 and 40:60 respectively. The level of water absorption of quartzite is higher as compared to granite and basalt.

The dry density for upper and lower limit gradations of all the aggregates is within the range between 2.16-2.38, where there is not much difference in the dry density values. It can be concluded that the density of the aggregates is not affected by the aggregate gradation. The dry density value for basalt is higher compared to granite and quartzite.

Table 3 - Wet mix road base gradation limit according to PWD Specifications and for selected aggregates

Sieve Size (mm)	Lower Limit	Upper Limit	Aggregate Types		
			Basalt	Granite	Quartzite
50	100	100	100	100	100
37.5	95	100	98	97	98
20	60	80	74	70	76
10	40	60	54	52	56
5	25	40	34	34	32
2.36	15	30	21	27	21
0.6	8	22	10	14	10
0.075	0	8	2	5	2
Pan	-	-	-	-	-

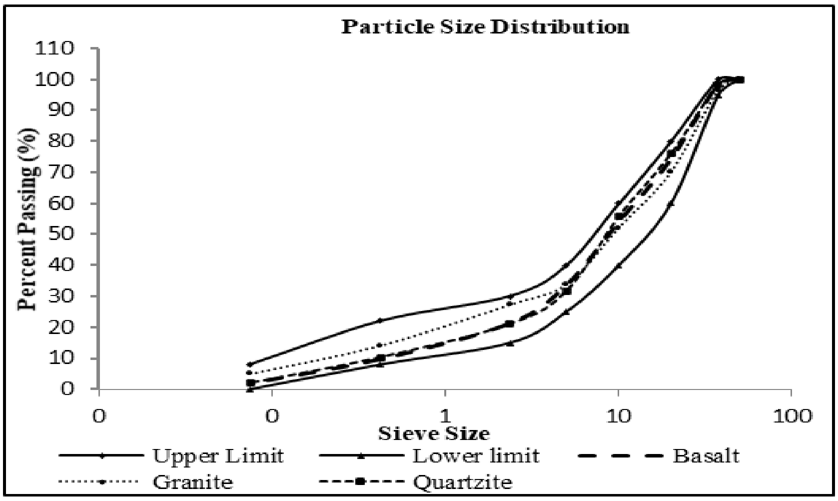


Fig. 1 - Particle size distribution for upper and lower limit gradations

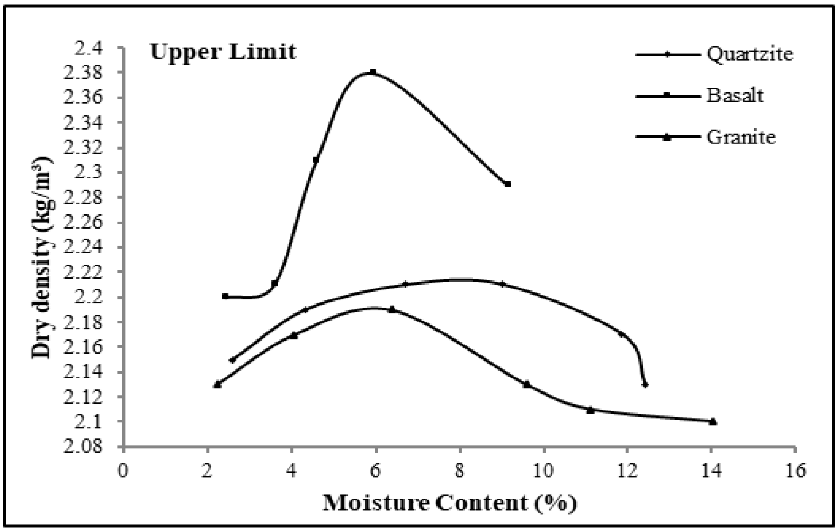


Fig. 2 - Compaction curves for upper limit gradation

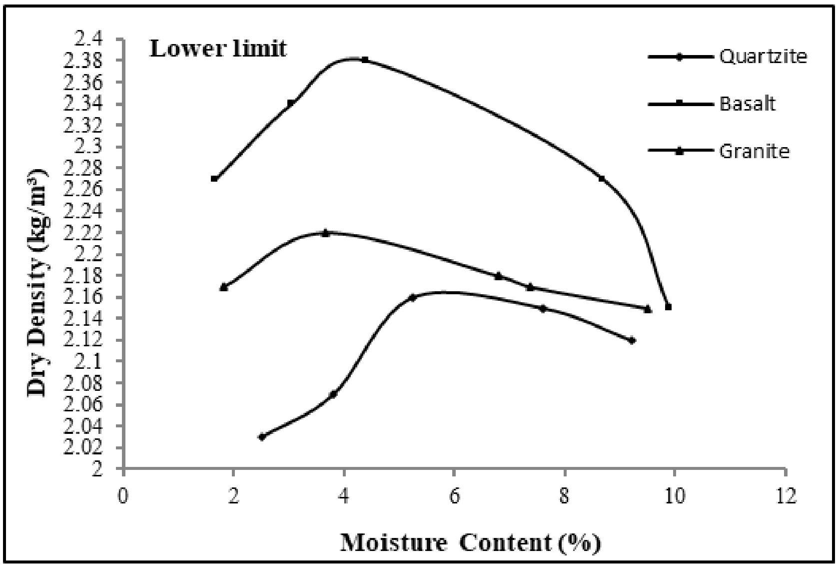


Fig. 3 - Compaction curves for lower limit gradation

Table 4 - Compaction characteristics of the aggregates

Aggregate Types	Upper Limit		Lower Limit	
	W_{opt} (%)	Υd_{max} (kg/cm^3)	W_{opt} (%)	Υd_{max} (kg/cm^3)
Basalt	5.8	2.38	4.2	2.38
Granite	6.0	2.20	3.7	2.22
Quartzite	8.2	2.22	5.7	2.16

(W_{opt}= Optimum moisture content, Υd_{max}=Maximum dry density)

2.4 Relative Density and Water Absorption (AASTHOT85)

The specific gravity of aggregates used in road construction ranges between 2.5 to 3.0 with an average of about 2.68 [16]. Water absorption is the percentage of water in the pores of the aggregates after being immersed in the water. Table 5 shows the results from the relative density test which was carried out on the selected aggregates. The specific gravity values of these aggregates are within the range, meanwhile for water absorption quartzite showed a higher percentage compared to basalt and granite.

Table 5 - Relative density and water absorption test results

Aggregate Types/ Tests	Basalt	Granite	Quartzite
The particle Density on An Oven-Dried Basis, Mg/m³	2.65	2.63	2.48
The Apparent Particle Density on A Saturated and Surface-Dried Basis, Mg/m³	2.66	2.64	2.49
The Apparent Particle Density, Mg/m³	2.68	2.65	2.58
The Water Absorption (As % of Dry Mass)	0.37	0.38	1.64

2.5 California Bearing Ratio (CBR) Test

CBR test is a widely used empirical penetration type test for aggregates and construction materials. CBR is the most adaptable method as it can be carried out on most types of soil ranging from heavy to gravel type of materials. CBR test provides an indirect measurement of shear strength, and it is dependent on moisture content and level of compaction. CBR is the ratio of force per unit area required to penetrate soil or gravel with a circular plunger of 50mm diameter at the rate of 1.25mm/min.

The test was carried out according to the PWD road work specification at compaction of 95% of the maximum dry density for all samples under CBR soaked and un-soaked conditions at different gradation, the upper and lower limit of PWD road specification gradation in respect of wet-mix road base. The specimens were tested under the worst conditions (soaked in water for 96 hours) and un-soaked conditions. The load readings at the penetrations of 0,0.5, 1.0, 1.5,2.0,2.5,3.0,3.5,4.0,4.5,5.0,5.5,6.0,6.5,7.0 and 7.5mm were recorded and the results of stress versus penetration depth were plotted as shown in Fig. 4 and Fig. 5.

All three aggregates, basalt, granite, and quartzite with lower limit gradations showed higher stress values under both, soaked and un-soaked conditions. Granite achieved the highest stress value, followed by basalt and quartzite for lower limit gradations under soaked conditions, and for un-soaked conditions the highest stress value was achieved by granite, followed by quartzite and basalt.

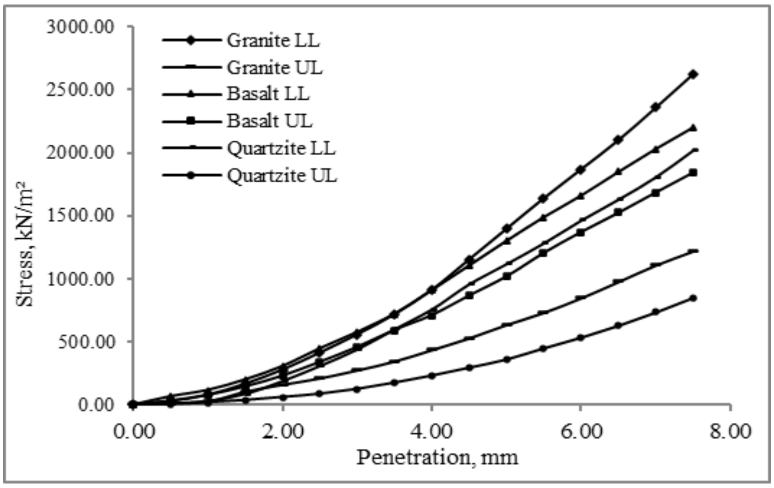


Fig. 4 - Stress versus penetration of CBR test of soaked samples

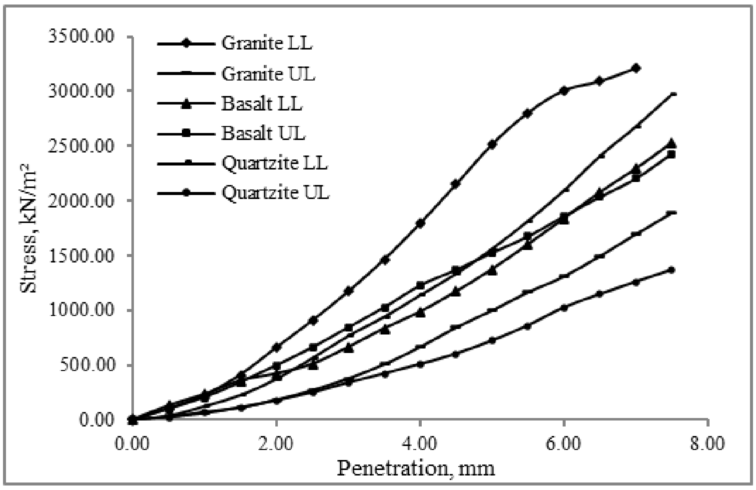


Fig. 5 - Stress versus penetration of CBR test of un-soaked samples

The results presented in Fig. 6 and Fig. 7 show that the variation in lower and upper limit gradations has a significant effect on the strength of the selected aggregates. It can be concluded that the strength of the aggregates not only depends on the type of aggregates but also on the changes in the aggregation in allowed range.

According to the PWD Road Works Specifications, the required CBR value for road base materials should be more than 80% as shown in Table 1. Fig. 6 and Fig. 7 show the CBR value for all the samples prepared under soaked and un-soaked conditions of upper and limit gradation for basalt (B1, B2, B3), granite (G1, G2, G3), and quartzite (Q1, Q2, Q3). A comparison between CBR results reveals that the difference between the highest and lowest value for lower limit gradations is 24.75% on average and 59.98% on average for upper limit gradations under soaked conditions. Meanwhile, for un-soaked, the difference between the highest and lowest is 87.15% on average for the lower limit and 57.36% on average for upper limit gradation.

2.6 Relationship Between CBR Value with Moisture Content and Density

In general, the parameters presenting the largest correlations with the CBR test are the dry density (γd) and water content (w). These correlations could be observed in Fig. 8(a)-(d). Table 6 summarizes the values of coefficient R^2 for each of the aggregates for both γd and w.

In the case of all the aggregates, CBR values correlated linearly with parameters with γd and w. For basalt, CBR correlated linearly with the parameters: (i) γd with $R^2 = 0.8616$, and (ii) $w = 0.8646$ for lower limit gradation, and (iii) $\gamma d = 0.6915$ and $w = 0.2475$ for upper limit gradation. Aggregate granite showed linear relationship with: $\gamma d = 0.5229$

and w = 0.1336 for lower limit gradation and γd = 0.0194 and w = 0.9957 for upper limit gradation. Meanwhile for aggregate quartzite showed linear relationships with: (i) γd = 0.8359, and (ii) w = 0.1788 for lower limit gradation and, (iii) γd = 0.7682 and w = 0.5257 for upper limit gradation.

The result in Table 6, shows that dry density influenced the results of basalt and quartzite compared with water content. The largest correlation of parameters was obtained for granite, which is water content for upper limit gradation.

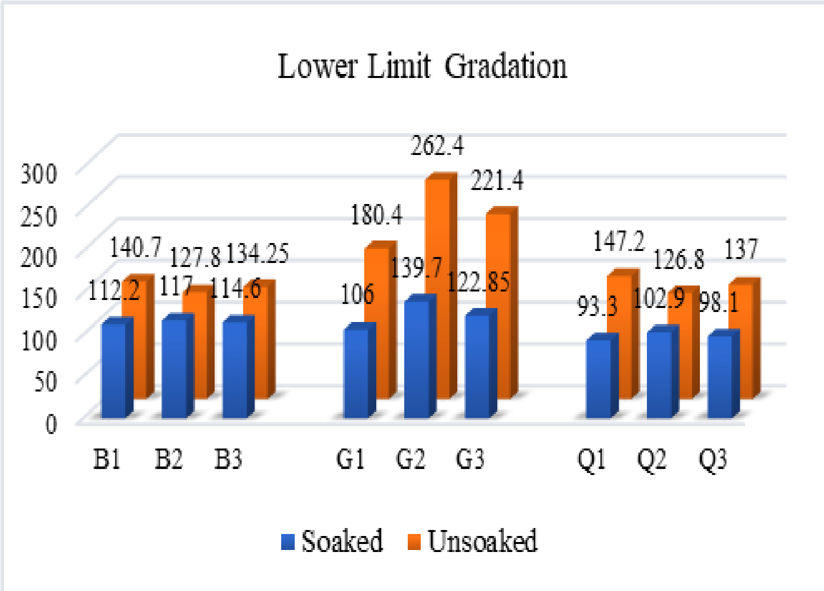


Fig. 6 - CBR value for lower limit gradation

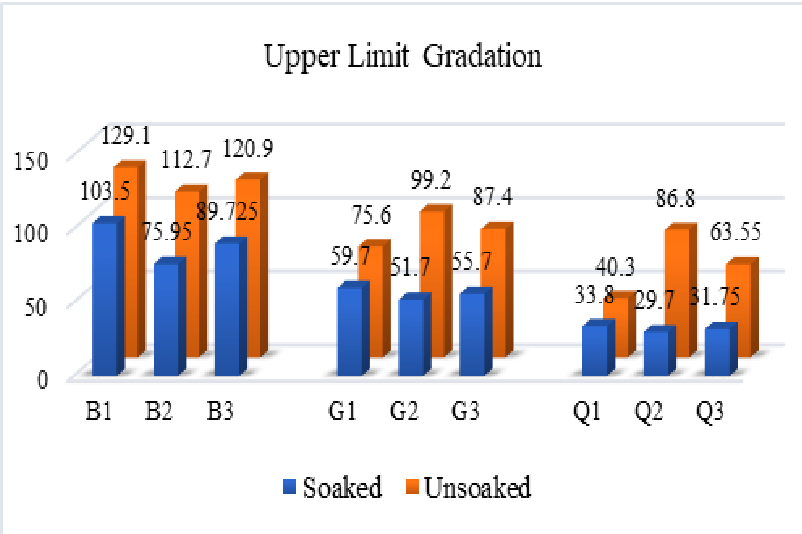
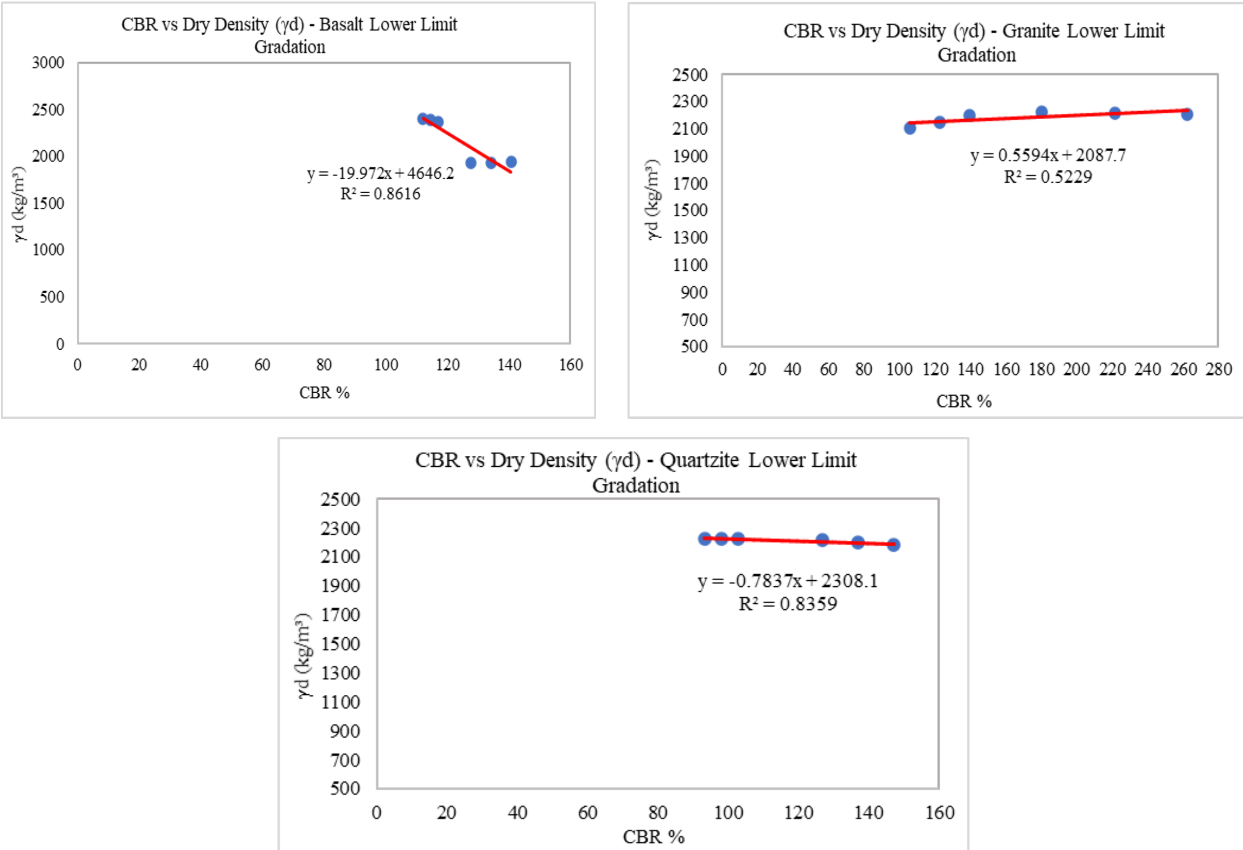


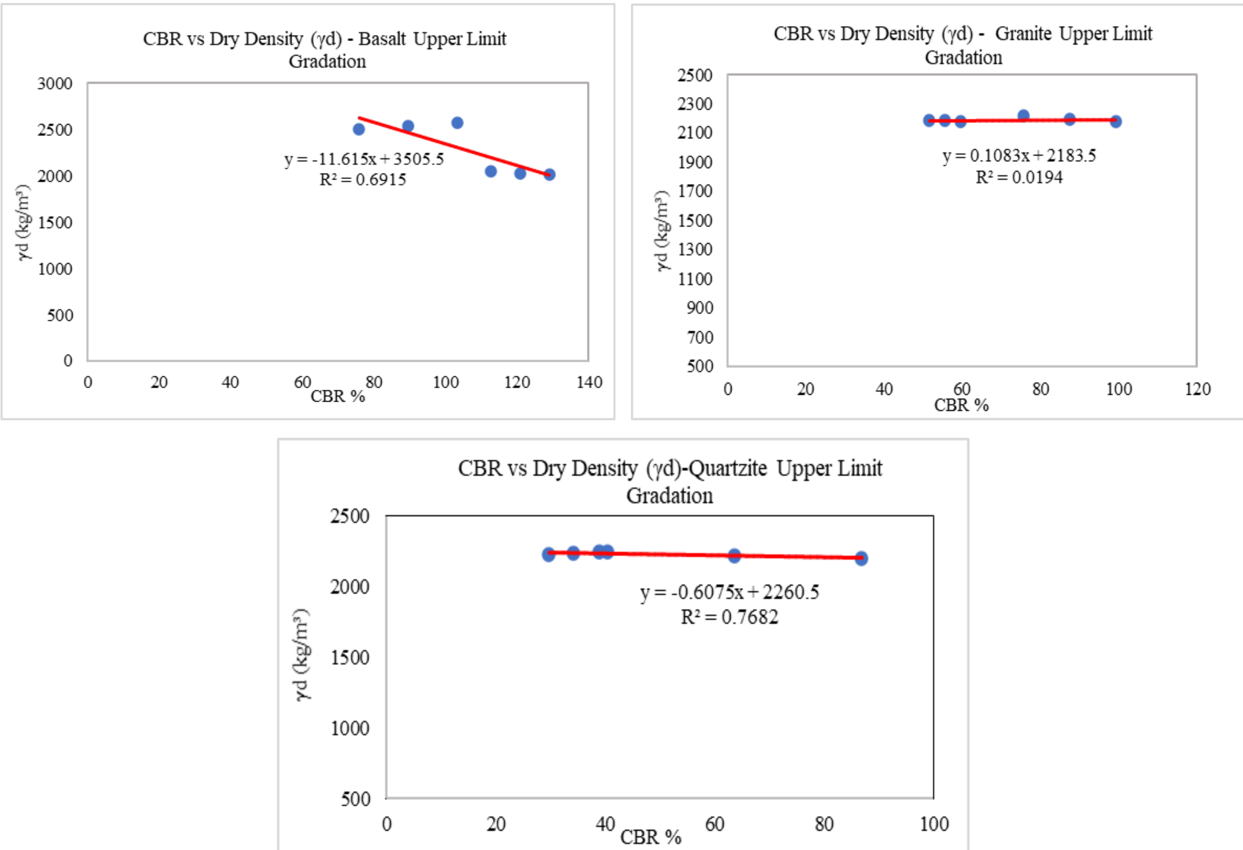
Fig. 7 - CBR value for upper limit gradation

Table 6 - Coefficient R^2 for the correlations of CBR values and aggregates parameters for different gradation limits

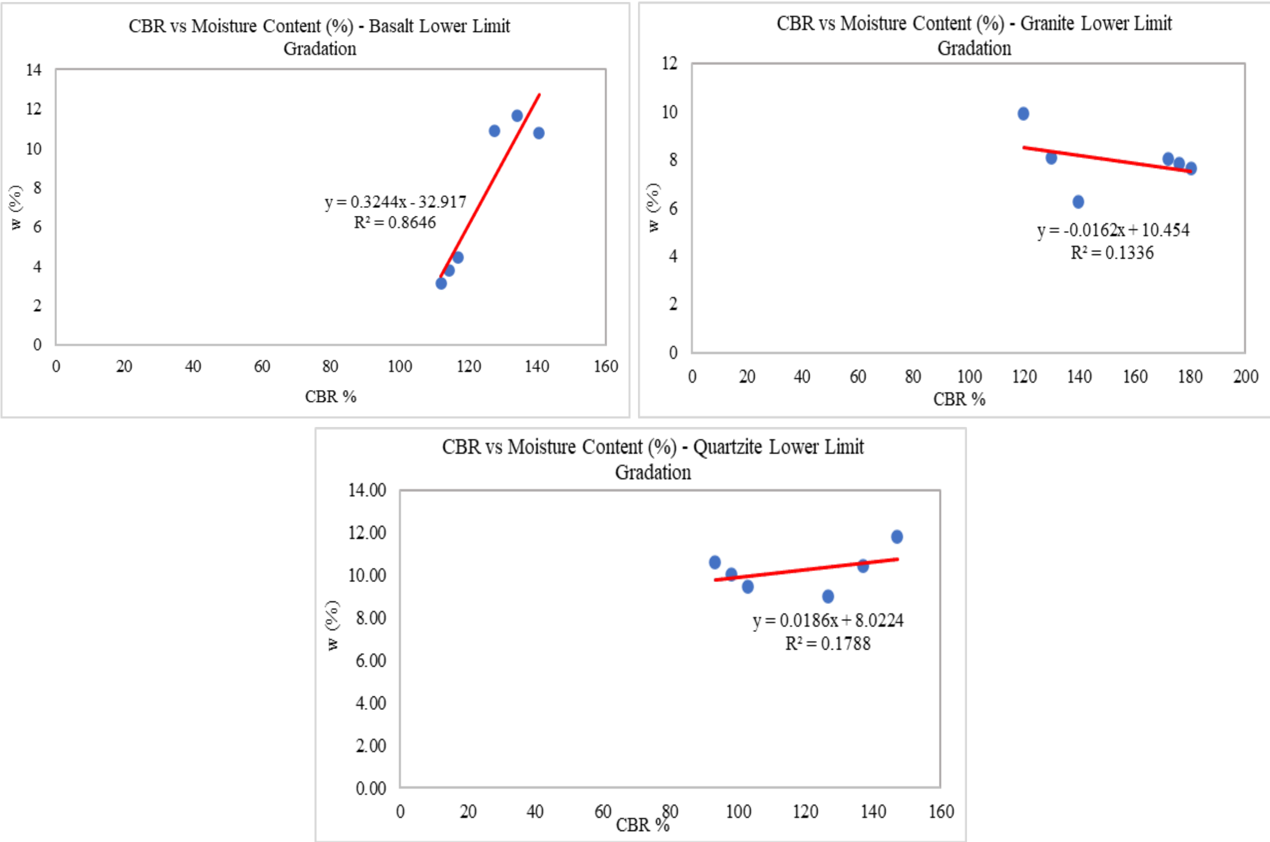
Type of Aggregate	Lower Limit Gradation		Upper Limit Gradation	
	γd (kg/m³)	w (%)	γd (kg/m³)	w (%)
Basalt	0.8616	0.8646	0.6915	0.2475
Granite	0.5229	0.1336	0.0194	0.9957
Quartzite	0.8359	0.1788	0.7682	0.5257


CBR vs Dry Density (γd) - Basalt Lower Limit Gradation
y = -19.972x + 4646.2
R² = 0.8616
γd (kg/m³)
CBR %
CBR vs Dry Density (γd) - Granite Lower Limit Gradation
y = 0.5594x + 2087.7
R² = 0.5229
γd (kg/m³)
CBR %
CBR vs Dry Density (γd) - Quartzite Lower Limit Gradation
y = -0.7837x + 2308.1
R² = 0.8359
γd (kg/m³)
CBR %

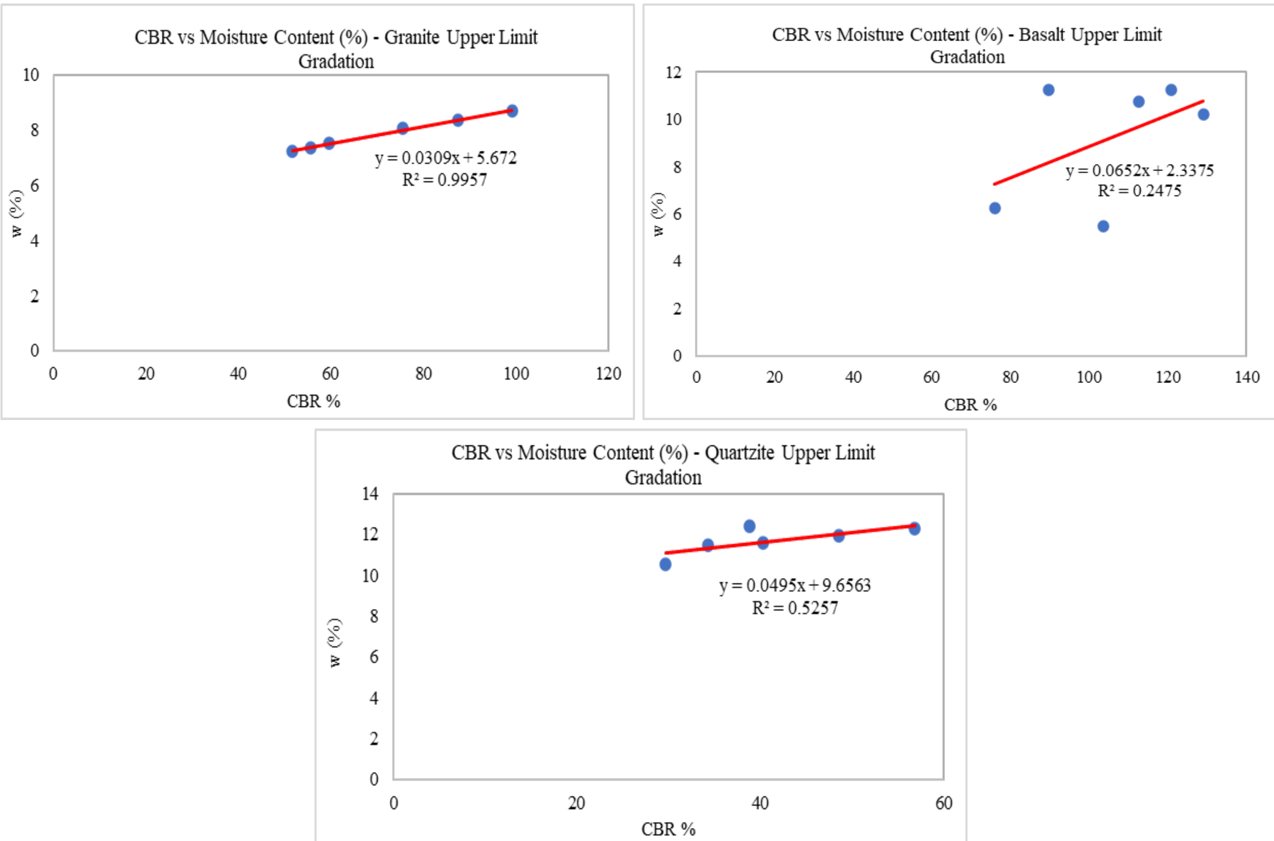
(a)


CBR vs Dry Density (γd) - Basalt Upper Limit Gradation
y = -11.615x + 3505.5
R² = 0.6915
γd (kg/m³)
CBR %
CBR vs Dry Density (γd) - Granite Upper Limit Gradation
y = 0.1083x + 2183.5
R² = 0.0194
γd (kg/m³)
CBR %
CBR vs Dry Density (γd)-Quartzite Upper Limit Gradation
y = -0.6075x + 2260.5
R² = 0.7682
γd (kg/m³)
CBR %

(b)



(c)



(d)

Fig. 8 - Parameters influencing bearing ratio (CBR) values (a) materials *γd* for lower limit gradation; (b) materials *γd* for upper limit gradation; (c) materials *w* for lower limit gradation, and; (d) materials *w* for upper limit gradation

3. Conclusions

The aggregates used for this study meets the PWD Road Works Specifications for wet mix road base materials. All the physical properties test results which have been conducted indicated that the material is sufficient to meet both standards, PWD and AASTHO, and the particle size distribution analysis of the aggregates showed that the materials meet the grading requirements. The Atterberg limit test found that the LL value of all the three types of aggregates is below 25, which meets the requirements for road base materials according to AASTHO Standards. The plasticity indexes of the materials were identified as non-plastic. Through the compaction test, the maximum dry density and optimum moisture content of the aggregates were obtained. Basalt showed higher density but lower moisture content, compared with granite and quartzite. Higher fines content which is 60% in upper limit gradation resulted in higher optimum moisture content, compared to 40% fines content in lower limit gradation.

For soaked and un-soaked conditions, the samples with lower limit gradations obtained higher stress values compared to the samples with upper limit gradations. Basically, the ratio of coarse aggregates to fine aggregates for lower limit gradation was 60/40; meanwhile for upper limit gradation was 40/60. The CBR value for the samples with lower limit gradations are more than 80% compared to the samples with upper limit gradation for both, soaked and un-soaked conditions. A comparison of the upper and lower limits of gradation indicates that this effect is considerable and changes in gradations greatly affect the CBR value. Lower limit gradation with higher maximum particle sizes and low fines content provide higher CBR value compared with the upper limit gradation with lower maximum particle sizes. Therefore, as the maximum particle size increases, the fines will fill the voids, thus the interlocking of the aggregates generate stronger bond between the coarse and fines aggregates. When larger particles are lower than fines, the interlocking of the coarse aggregates will be less and the voids will be filled up by the fines, thus when there is a load applied, the fines tend to move and results in lower strength. Further study may be made on more different levels of gradations to determine the significant level between CBR value with moisture and density.

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